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(54) **ANTENNA WITH TUNABLE HIGH BAND PARASITIC ELEMENT**

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CPC ***H01Q 5/0024*** (2013.01); ***H01Q 1/243*** (2013.01); ***H01Q 5/30*** (2015.01); ***H01Q 5/321*** (2015.01); ***H01Q 5/378*** (2015.01); ***H01Q 9/0421*** (2013.01)

(58) **Field of Classification Search**
USPC .... 343/700 MS, 702, 745, 833
See application file for complete search history.

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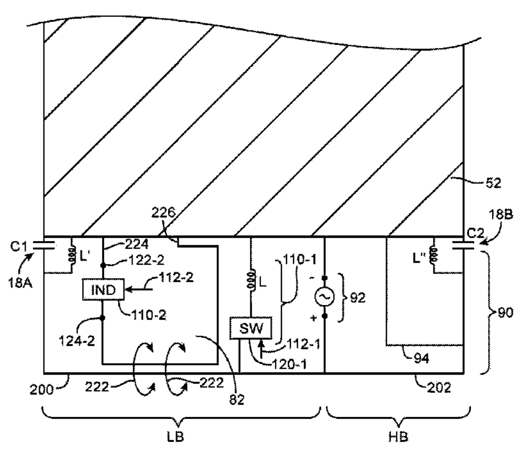
(57) **ABSTRACT**

Electronic devices may be provided that include radio-frequency transceiver circuitry and antennas. An antenna may be formed from an antenna resonating element and an antenna ground. The antenna resonating element may have a shorter portion that resonates at higher communications band frequencies and a longer portion that resonates at lower communications band frequencies. The resonating element may be formed from a peripheral conductive electronic device housing structure that is separated from the antenna ground by an opening. A parasitic monopole antenna resonating element or parasitic loop antenna resonating element may be located in the opening. Antenna tuning in the higher communications band may be implemented using an adjustable inductor in the parasitic element. Antenna tuning in the lower communications band may be implemented using an adjustable inductor that couples the antenna resonating element to the antenna ground.

17 Claims, 9 Drawing Sheets



(51) **Int. Cl.**

H01Q 9/04	(2006.01)
H01Q 5/30	(2015.01)
H01Q 5/321	(2015.01)
H01Q 5/378	(2015.01)

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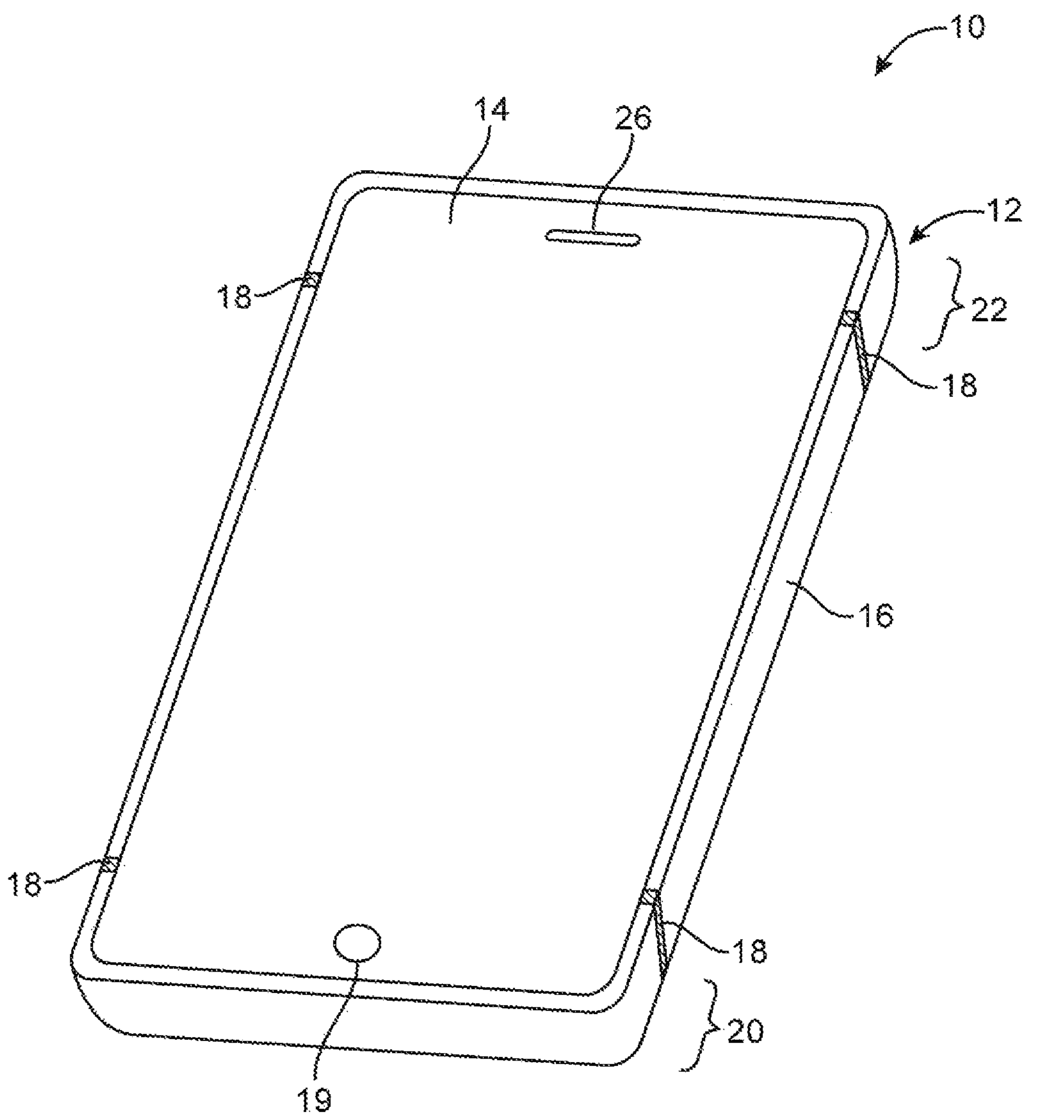
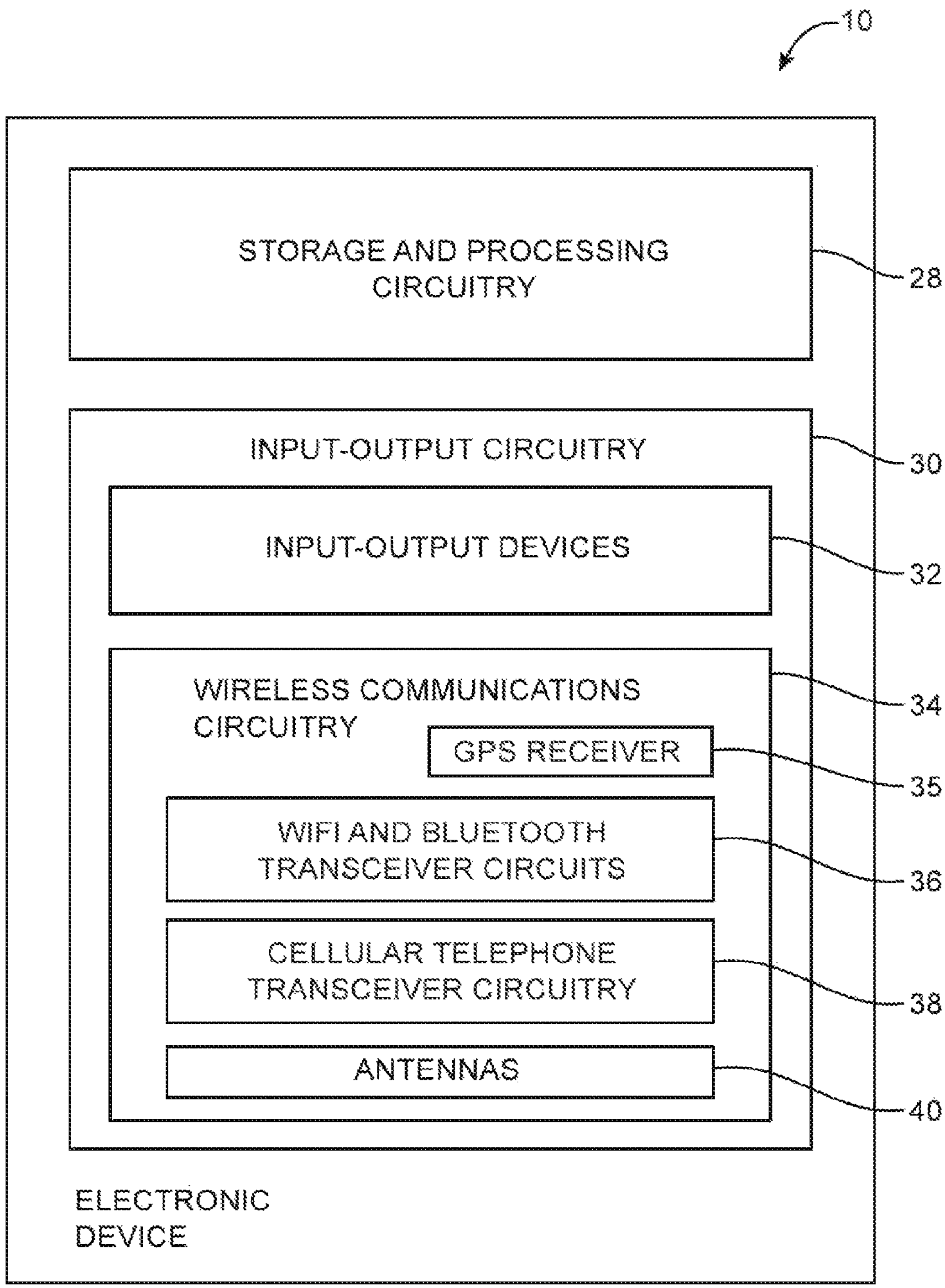


FIG. 1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STORAGE AND PROCESSING CIRCUITRY
28
INPUT-OUTPUT CIRCUITRY
30
INPUT-OUTPUT DEVICES
32
WIRELESS COMMUNICATIONS CIRCUITRY
34
GPS RECEIVER
35
WIFI AND BLUETOOTH TRANSCEIVER CIRCUITS
36
CELLULAR TELEPHONE TRANSCEIVER CIRCUITRY
38
ANTENNAS
40
ELECTRONIC DEVICE

FIG. 2

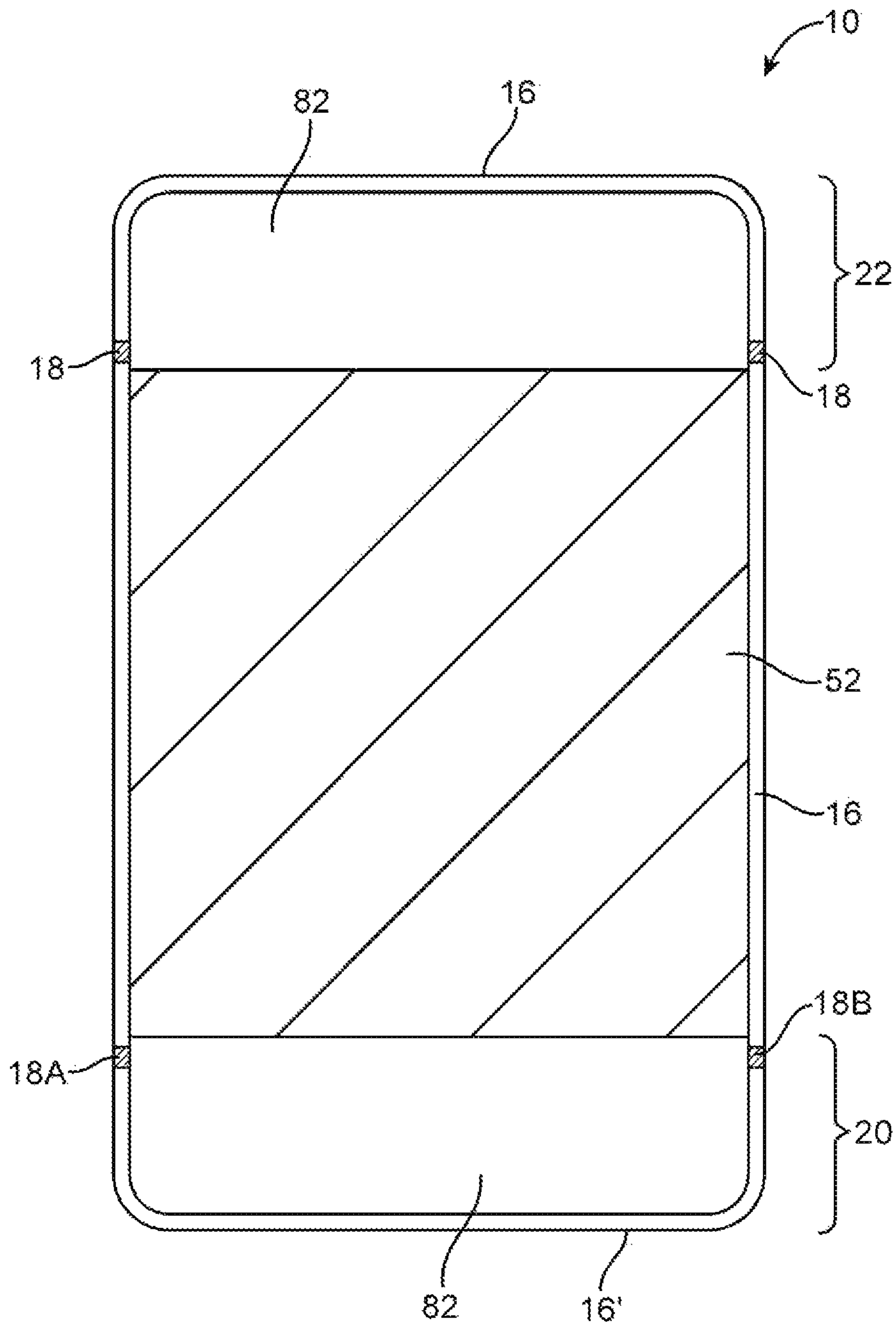


FIG. 3

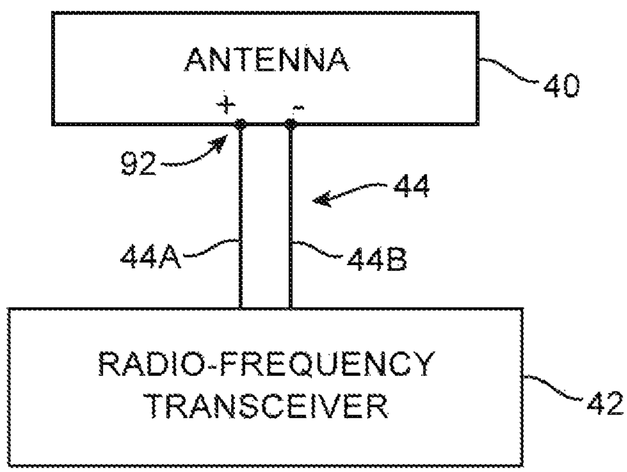


FIG. 4

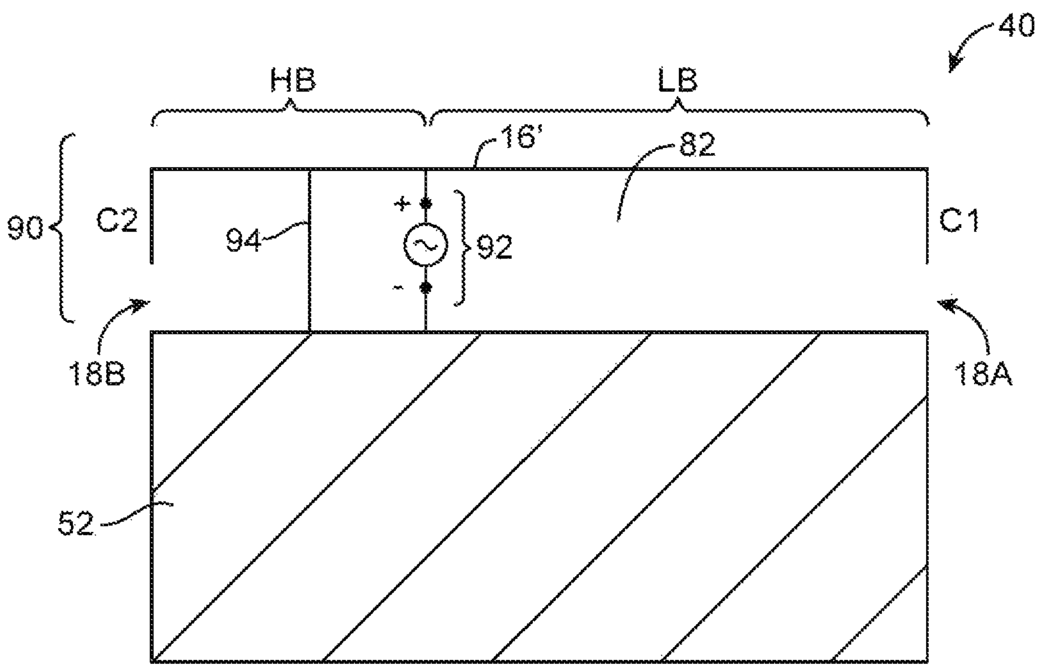


FIG. 5

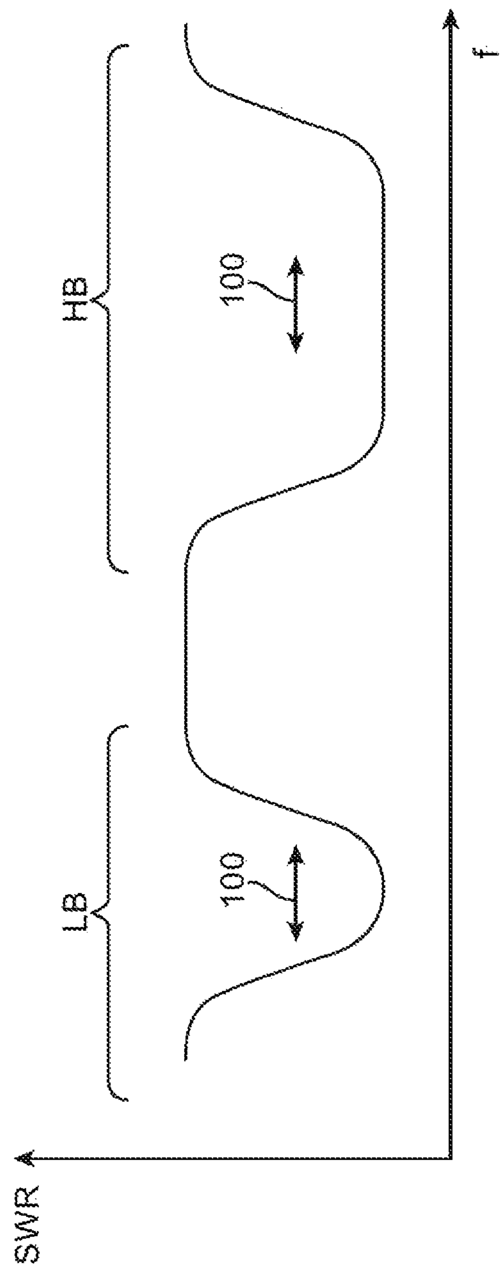


FIG. 6

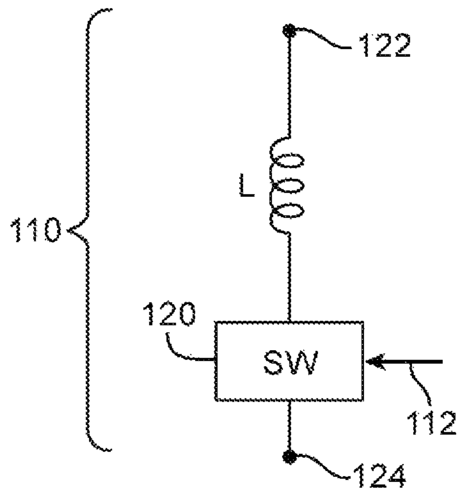


FIG. 7

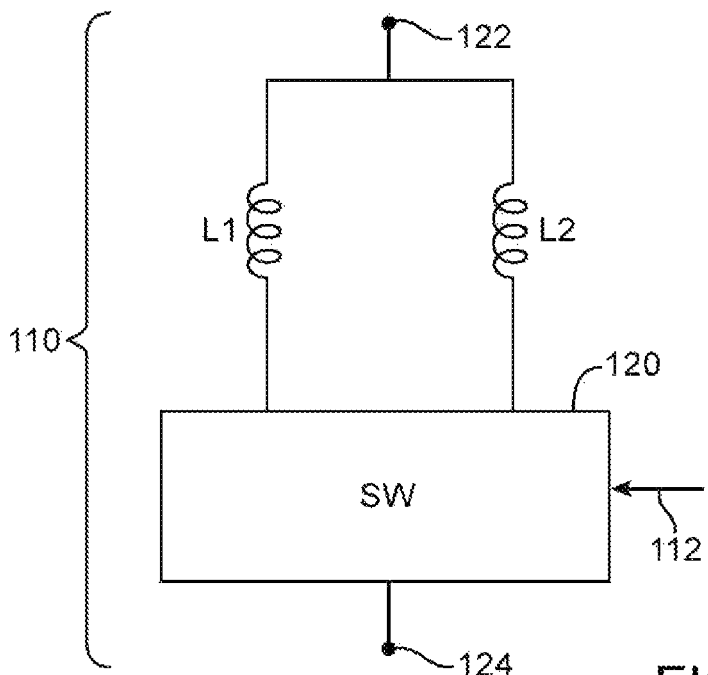
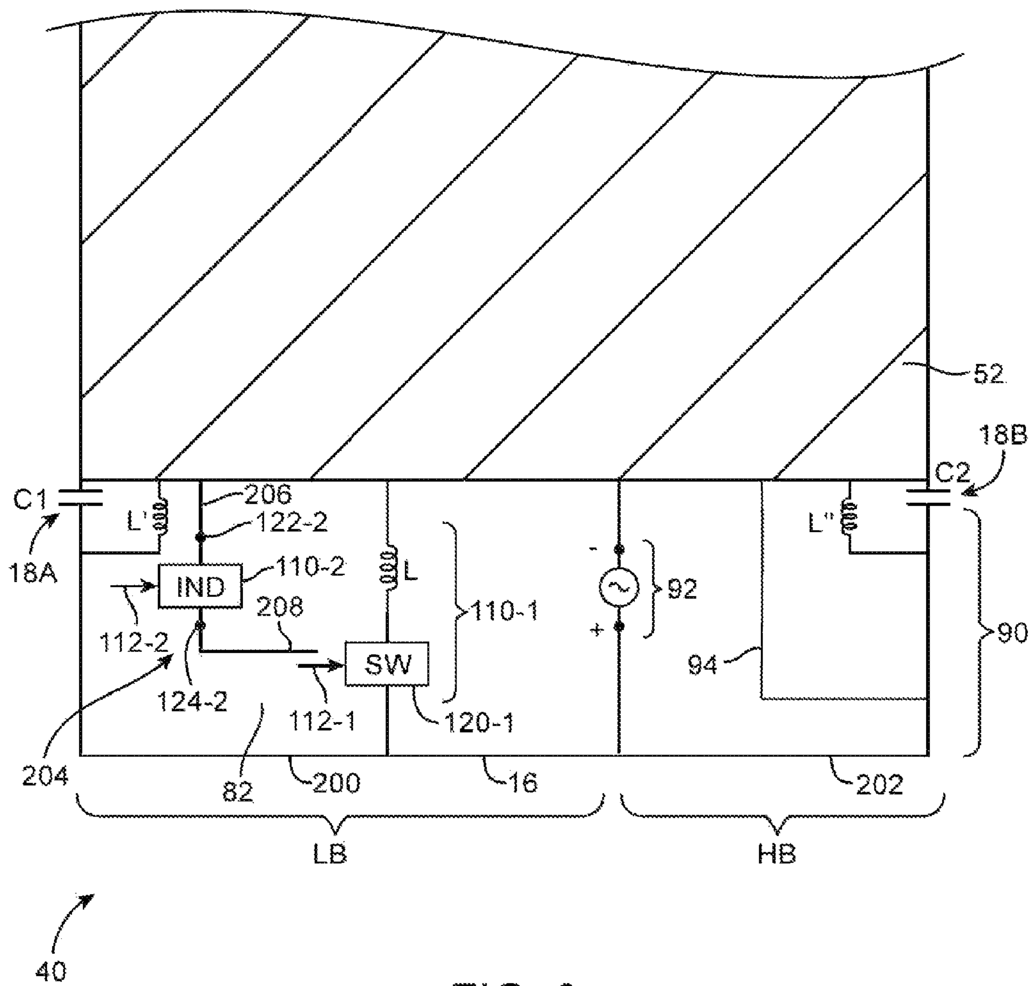


FIG. 8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C1
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FIG. 9

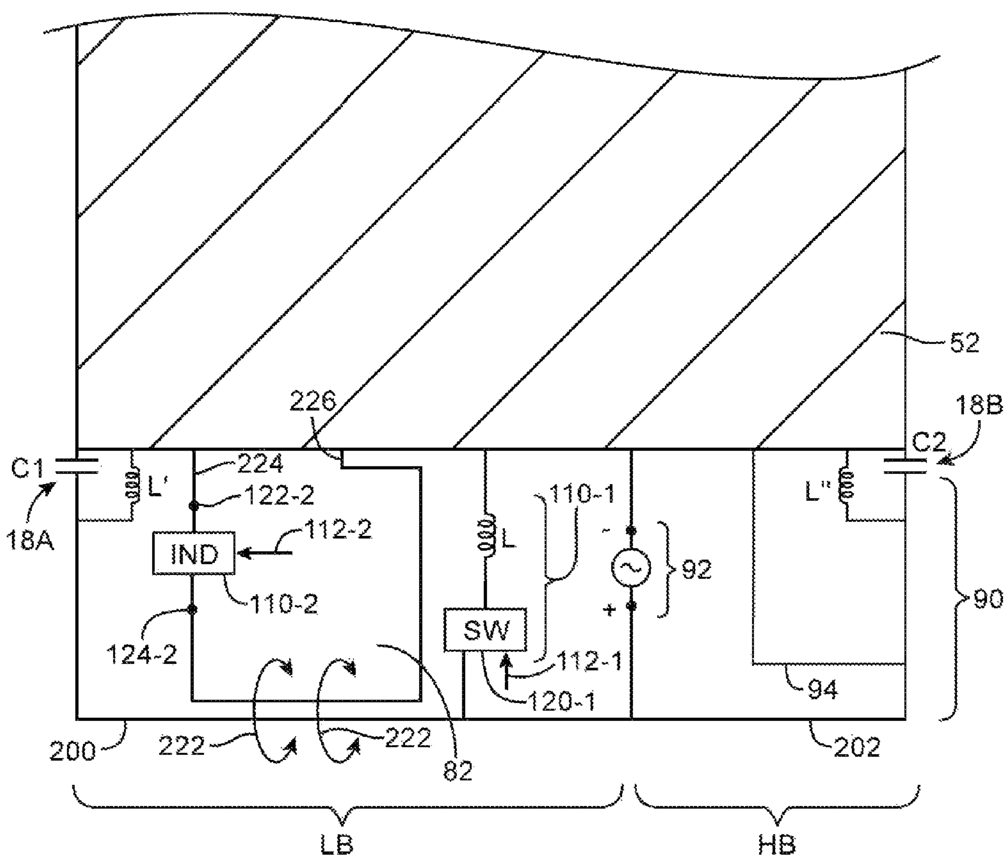

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FIG. 10

ANTENNA WITH TUNABLE HIGH BAND PARASITIC ELEMENT

BACKGROUND

This relates generally to electronic devices, and more particularly, to antennas for electronic devices with wireless communications circuitry.

Electronic devices such as portable computers and cellular telephones are often provided with wireless communications capabilities. For example, electronic devices may use long-range wireless communications circuitry such as cellular telephone circuitry to communicate using cellular telephone bands. Electronic devices may use short-range wireless communications circuitry such as wireless local area network communications circuitry to handle communications with nearby equipment. Electronic devices may also be provided with satellite navigation system receivers and other wireless circuitry.

To satisfy consumer demand for small form factor wireless devices, manufacturers are continually striving to implement wireless communications circuitry such as antenna components using compact structures. At the same time, it may be desirable to include conductive structures in an electronic device such as metal device housing components. Because conductive structures can affect radio-frequency performance, care must be taken when incorporating antennas into an electronic device that includes conductive structures. Moreover, care must be taken to ensure that the antennas and wireless circuitry in a device are able to exhibit satisfactory performance over a range of operating frequencies.

It would therefore be desirable to be able to provide improved wireless communications circuitry for wireless electronic devices.

SUMMARY

Electronic devices may be provided that contain wireless communications circuitry. The wireless communications circuitry may include radio-frequency transceiver circuitry and antennas. An antenna may be formed from an antenna resonating element arm and an antenna ground. The antenna resonating element arm may have a shorter portion that resonates at higher communications band frequencies and a longer portion that resonates at lower communications band frequencies. The resonating element arm may be formed from a peripheral conductive electronic device housing structure that is separated from the antenna ground by an opening.

A parasitic monopole antenna resonating element or parasitic loop antenna resonating element may be located in the opening. Antenna tuning in the higher communications band may be implemented using an adjustable inductor in the parasitic element. Antenna tuning in the lower communications band may be implemented using an adjustable inductor that couples the antenna resonating element to the antenna ground.

Further features of the invention, its nature and various advantages will be more apparent from the accompanying drawings and the following detailed description of the preferred embodiments.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a perspective view of an illustrative electronic device with wireless communications circuitry in accordance with an embodiment of the present invention.

FIG. **2** is a schematic diagram of an illustrative electronic device with wireless communications circuitry in accordance with an embodiment of the present invention.

FIG. **3** is a top view of an illustrative electronic device of the type shown in FIG. **1** in which antennas may be formed using conductive housing structures such as portions of a peripheral conductive housing member in accordance with an embodiment of the present invention.

FIG. **4** is a circuit diagram showing how an antenna in the electronic device of FIG. **1** may be coupled to radio-frequency transceiver circuitry in accordance with an embodiment of the present invention.

FIG. **5** is a diagram of an illustrative antenna having an antenna resonating element of the type that may be formed from a segment of a peripheral conductive housing member and that has portions that support communications in low and high bands in accordance with an embodiment of the present invention.

FIG. **6** is a graph in which antenna performance for a dual band inverted-F antenna has been plotted as a function of operating frequency in accordance with an embodiment of the present invention.

FIG. **7** is a diagram of an illustrative adjustable inductor based on a single fixed inductor that may be used in a tunable antenna in accordance with an embodiment of the present invention.

FIG. **8** is a diagram of an illustrative adjustable inductor based on multiple fixed inductors that may be used in a tunable antenna in accordance with an embodiment of the present invention.

FIG. **9** is a diagram of an illustrative antenna having a parasitic monopole antenna resonating element and adjustable components for providing the antenna with tunable low and high band responses in accordance with an embodiment of the present invention.

FIG. **10** is a diagram of an illustrative antenna having a parasitic loop antenna resonating element and adjustable components for providing the antenna with tunable low and high band responses in accordance with an embodiment of the present invention.

DETAILED DESCRIPTION

Electronic devices such as electronic device **10** of FIG. **1** may be provided with wireless communications circuitry. The wireless communications circuitry may be used to support wireless communications in multiple wireless communications bands. The wireless communications circuitry may include one or more antennas.

The antennas can include loop antennas, inverted-F antennas, strip antennas, planar inverted-F antennas, slot antennas, hybrid antennas that include antenna structures of more than one type, or other suitable antennas. Conductive structures for the antennas may, if desired, be formed from conductive electronic device structures. The conductive electronic device structures may include conductive housing structures. The housing structures may include a peripheral conductive member that runs around the periphery of an electronic device. The peripheral conductive member may serve as a bezel for a planar structure such as a display, may serve as sidewall structures for a device housing, and/or may form other housing structures. Gaps in the peripheral conductive member may be associated with the antennas.

Electronic device **10** may be a portable electronic device or other suitable electronic device. For example, electronic device **10** may be a laptop computer, a tablet computer, a somewhat smaller device such as a wrist-watch device, pendant device, headphone device, earpiece device, or other wearable or miniature device, a cellular telephone, or a media player. Device **10** may also be a television, a set-top box, a desktop computer, a computer monitor into which a computer has been integrated, or other suitable electronic equipment.

Device **10** may include a housing such as housing **12**. Housing **12**, which may sometimes be referred to as a case, may be formed of plastic, glass, ceramics, fiber composites, metal (e.g., stainless steel, aluminum, etc.), other suitable materials, or a combination of these materials. In some situations, parts of housing **12** may be formed from dielectric or other low-conductivity material. In other situations, housing **12** or at least some of the structures that make up housing **12** may be formed from metal elements.

Device **10** may, if desired, have a display such as display **14**. Display **14** may, for example, be a touch screen that incorporates capacitive touch electrodes. Display **14** may include image pixels formed from light-emitting diodes (LEDs), organic LEDs (OLEDs), plasma cells, electrowetting pixels, electrophoretic pixels, liquid crystal display (LCD) components, or other suitable image pixel structures. A display cover layer formed from clear glass, transparent plastic, or other transparent dielectric may cover the surface of display **14**. Buttons such as button **19** may pass through openings in the display cover layer. The cover layer may also have other openings such as an opening for speaker port **26**.

Housing **12** may include a peripheral member such as member **16**. Member **16** may run around the periphery of device **10** and display **14**. In configurations in which device **10** and display **14** have a rectangular shape, member **16** may have a rectangular ring shape (as an example). Member **16** or part of member **16** may serve as a bezel for display **14** (e.g., a cosmetic trim that surrounds all four sides of display **14** and/or helps hold display **14** to device **10**). Member **16** may also, if desired, form sidewall structures for device **10** (e.g., by forming a metal band with vertical sidewalls surrounding the periphery of device **10**, etc.).

Member **16** may be formed of a conductive material and may therefore sometimes be referred to as a peripheral conductive member, peripheral conductive housing member, or conductive housing structures. Member **16** may be formed from a metal such as stainless steel, aluminum, or other suitable materials. One, two, or more than two separate structures (e.g., segments) may be used in forming member **16**.

It is not necessary for member **16** to have a uniform cross-section. For example, the top portion of member **16** may, if desired, have an inwardly protruding lip that helps hold display **14** in place. If desired, the bottom portion of member **16** may also have an enlarged lip (e.g., in the plane of the rear surface of device **10**). In the example of FIG. **1**, member **16** has substantially straight vertical sidewalls. This is merely illustrative. The sidewalls of member **16** may be curved or may have any other suitable shape. In some configurations (e.g., when member **16** serves as a bezel for display **14**), member **16** may run around the lip of housing **12** (i.e., member **16** may cover only the edge of housing **12** that surrounds display **14** and not the rear edge of housing **12** of the sidewalls of housing **12**). Integral portions of the metal structure that forms member **16** may, if desired, extend across the rear of device **10** (e.g., housing **12** may have a planar rear portion and portions of peripheral conductive member **16** may be formed from sidewall portions of that extend vertically upwards from the planar rear portion).

Display **14** may include conductive structures such as an array of capacitive electrodes, conductive lines for addressing pixel elements, driver circuits, etc. Housing **12** may include internal structures such as metal frame members, a planar housing member (sometimes referred to as a midplate) that spans the walls of housing **12** (i.e., a substantially rectangular member that is welded or otherwise connected between opposing sides of member **16**), printed circuit boards, and other internal conductive structures. These conductive structures may be located in the center of housing **12** under display **14** (as an example).

In regions **22** and **20**, openings may be formed within the conductive structures of device **10** (e.g., between peripheral conductive member **16** and opposing conductive structures such as conductive housing structures, a conductive ground plane associated with a printed circuit board, and conductive electrical components in device **10**). These openings may be filled with air, plastic, and other dielectrics. Conductive housing structures and other conductive structures in device **10** may serve as a ground plane for the antennas in device **10**. The openings in regions **20** and **22** may serve as slots in open or closed slot antennas, may serve as a central dielectric region that is surrounded by a conductive path of materials in a loop antenna, may serve as a space that separates an antenna resonating element such as a strip antenna resonating element or an inverted-F antenna resonating element from the ground plane, or may otherwise serve as part of antenna structures formed in regions **20** and **22**.

In general, device **10** may include any suitable number of antennas (e.g., one or more, two or more, three or more, four or more, etc.). The antennas in device **10** may be located at opposing first and second ends of an elongated device housing, along one or more edges of a device housing, in the center of a device housing, in other suitable locations, or in one or more of such locations. The arrangement of FIG. **1** is merely illustrative.

Portions of member **16** may be provided with gap structures. For example, member **16** may be provided with one or more gaps such as gaps **18**, as shown in FIG. **1**. The gaps may be filled with dielectric such as polymer, ceramic, glass, air, other dielectric materials, or combinations of these materials. Gaps **18** may divide member **16** into one or more peripheral conductive member segments. There may be, for example, two segments of member **16** (e.g., in an arrangement with two gaps), three segments of member **16** (e.g., in an arrangement with three gaps), four segments of member **16** (e.g., in an arrangement with four gaps, etc.). The segments of peripheral conductive member **16** that are formed in this way may form parts of antennas in device **10**.

In a typical scenario, device **10** may have upper and lower antennas (as an example). An upper antenna may, for example, be formed at the upper end of device **10** in region **22**. A lower antenna may, for example, be formed at the lower end of device **10** in region **20**. The antennas may be used separately to cover identical communications bands, overlapping communications bands, or separate communications bands. The antennas may be used to implement an antenna diversity scheme or a multiple-input-multiple-output (MIMO) antenna scheme.

Antennas in device **10** may be used to support any communications bands of interest. For example, device **10** may include antenna structures for supporting local area network communications, voice and data cellular telephone communications, global positioning system (GPS) communications or other satellite navigation system communications, Bluetooth® communications, etc.

A schematic diagram of an illustrative configuration that may be used for electronic device **10** is shown in FIG. **2**. As shown in FIG. **2**, electronic device **10** may include control circuitry such as storage and processing circuitry **28**. Storage and processing circuitry **28** may include storage such as hard disk drive storage, nonvolatile memory (e.g., flash memory or other electrically-programmable-read-only memory configured to form a solid state drive), volatile memory (e.g., static or dynamic random-access-memory), etc. Processing circuitry in storage and processing circuitry **28** may be used to control the operation of device **10**. The processing circuitry may be based on one or more microprocessors, microcontrollers, digital signal processors, baseband processors, power management units, audio codec chips, application specific integrated circuits, etc.

Storage and processing circuitry **28** may be used to run software on device **10**, such as internet browsing applications, voice-over-internet-protocol (VOIP) telephone call applications, email applications, media playback applications, operating system functions, etc. To support interactions with external equipment, storage and processing circuitry **28** may be used in implementing communications protocols. Communications protocols that may be implemented using storage and processing circuitry **28** include internet protocols, wireless local area network protocols (e.g., IEEE 802.11 protocols—sometimes referred to as WiFi®), protocols for other short-range wireless communications links such as the Bluetooth® protocol, cellular telephone protocols, etc.

Circuitry **28** may be configured to implement control algorithms that control the use of antennas in device **10**. For example, circuitry **28** may perform signal quality monitoring operations, sensor monitoring operations, and other data gathering operations and may, in response to the gathered data and information on which communications bands are to be used in device **10**, control which antenna structures within device **10** are being used to receive and process data and/or may adjust one or more switches, tunable elements, or other adjustable circuits in device **10** to adjust antenna performance. As an example, circuitry **28** may control which of two or more antennas is being used to receive incoming radio-frequency signals, may control which of two or more antennas is being used to transmit radio-frequency signals, may control the process of routing incoming data streams over two or more antennas in device **10** in parallel, may tune an antenna to cover a desired communications band, etc. In performing these control operations, circuitry **28** may open and close switches, may turn on and off receivers and transmitters, may adjust impedance matching circuits, may configure switches in front-end-module (FEM) radio-frequency circuits that are interposed between radio-frequency transceiver circuitry and antenna structures (e.g., filtering and switching circuits used for impedance matching and signal routing), may adjust switches, tunable circuits, and other adjustable circuit elements that are formed as part of an antenna or that are coupled to an antenna or a signal path associated with an antenna, and may otherwise control and adjust the components of device **10**.

Input-output circuitry **30** may be used to allow data to be supplied to device **10** and to allow data to be provided from device **10** to external devices. Input-output circuitry **30** may include input-output devices **32**. Input-output devices **32** may include touch screens, buttons, joysticks, click wheels, scrolling wheels, touch pads, key pads, keyboards, microphones, speakers, tone generators, vibrators, cameras, sensors, light-emitting diodes and other status indicators, data ports, etc. A user can control the operation of device **10** by supplying commands through input-output devices **32** and may receive status information and other output from device **10** using the output resources of input-output devices **32**.

Wireless communications circuitry **34** may include radio-frequency (RF) transceiver circuitry formed from one or more integrated circuits, power amplifier circuitry, low-noise input amplifiers, passive RF components, one or more antennas, and other circuitry for handling RF wireless signals. Wireless signals can also be sent using light (e.g., using infrared communications).

Wireless communications circuitry **34** may include satellite navigation system receiver circuitry such as Global Positioning System (GPS) receiver circuitry **35** (e.g., for receiving satellite positioning signals at 1575 MHz) or satellite navigation system receiver circuitry associated with other satellite navigation systems. Transceiver circuitry **36** may handle wireless local area network communications. For example, transceiver circuitry **36** may handle 2.4 GHz and 5 GHz bands for WiFi® (IEEE 802.11) communications and may handle the 2.4 GHz Bluetooth® communications band. Circuitry **34** may use cellular telephone transceiver circuitry **38** for handling wireless communications in cellular telephone bands such as bands in frequency ranges of about 700 MHz to about 2700 MHz or bands at higher or lower frequencies. Wireless communications circuitry **34** can include circuitry for other short-range and long-range wireless links if desired. For example, wireless communications circuitry **34** may include wireless circuitry for receiving radio and television signals, paging circuits, etc. In WiFi® and Bluetooth® links and other short-range wireless links, wireless signals are typically used to convey data over tens or hundreds of feet. In cellular telephone links and other long-range links, wireless signals are typically used to convey data over thousands of feet or miles.

Wireless communications circuitry **34** may include one or more antennas **40**. Antennas **40** may be formed using any suitable antenna types. For example, antennas **40** may include antennas with resonating elements that are formed from loop antenna structure, patch antenna structures, inverted-F antenna structures, closed and open slot antenna structures, planar inverted-F antenna structures, helical antenna structures, strip antennas, monopoles, dipoles, hybrids of these designs, etc. Different types of antennas may be used for different bands and combinations of bands. For example, one type of antenna may be used in forming a local wireless link antenna and another type of antenna may be used in forming a remote wireless link.

If desired, one or more of antennas **40** may be provided with tunable circuitry. The tunable circuitry may include switching circuitry based on one or more switches. The switching circuitry may, for example, include a switch that can be placed in an open or closed position. When control circuitry **28** of device **10** places the switch in its open position, an antenna may exhibit a first frequency response. When control circuitry **28** of device **10** places the switch in its closed position, the antenna may exhibit a second frequency response. Tunable circuitry for one or more of antennas **40** may also be based on switching circuitry that can switch selected circuit components into use. For example, an adjustable inductor may operate in a first mode in which a first inductor is switched into use and a second mode in which a second inductor is switched into use. An adjustable inductor may optionally also be switched into a mode in which a short circuit is switched into use or in which an open circuit is formed.

Using adjustable inductors such as these or other adjustable circuit components, the performance of antenna **40** may be adjusted in real time to cover operating frequencies of interest.

Antenna **40** may exhibit both a low band response and a high band response. As an example, antenna **40** may operate at low band communications frequencies from 700 MHz to 960 MHz and may operate at high band communications frequencies above 1710 MHz (e.g., from 1710-2700 MHz). Adjustment of the state of adjustable inductors or other adjustable circuit components may be used to tune the low band response of the antenna without appreciably affecting the high band response and may be used to tune the high band response of the antenna without appreciably affecting the low band response. The ability to adjust the low and/or high band responses of the antenna may allow the antenna to cover communications frequencies of interest.

A top interior view of device **10** in a configuration in which device **10** has a peripheral conductive housing member such as housing member **16** of FIG. **1** with one or more gaps **18** is shown in FIG. **3**. As shown in FIG. **3**, device **10** may have an antenna ground plane such as antenna ground plane **52**. Ground plane **52** may be formed from traces on printed circuit boards (e.g., rigid printed circuit boards and flexible printed circuit boards), from conductive planar support structures in the interior of device **10**, from conductive structures that form exterior parts of housing **12**, from conductive structures that are part of one or more electrical components in device **10** (e.g., parts of connectors, switches, cameras, speakers, microphones, displays, buttons, etc.), or other conductive device structures. Gaps such as gaps (openings) **82** may be filled with air, plastic, or other dielectric.

One or more segments of peripheral conductive member **16** may serve as antenna resonating elements for an antenna in device **10**. For example, the uppermost segment of peripheral conductive member **16** in region **22** may serve as an antenna resonating element for an upper antenna in device **10** and the lowermost segment of peripheral conductive member **16** in region **20** (i.e., segment **16'**, which extends between gap **18**A and gap **18**B) may serve as an antenna resonating element for a lower antenna in device **10**. The conductive materials of peripheral conductive member **16**, the conductive materials of ground plane **52**, and dielectric openings **82** (and gaps **18**) may be used in forming one or more antennas in device **10** such as an upper antenna in region **22** and a lower antenna in region **20**. Configurations in which an antenna in lower region **20** is implemented using a tunable frequency response configuration are sometimes described herein as an example.

FIG. **4** is a diagram showing how a radio-frequency signal path such as path **44** may be used to convey radio-frequency signals between antenna **40** and radio-frequency transceiver **42**. Antenna **40** may be one of antennas **40** of FIG. **2**. Radio-frequency transceiver **42** may be a receiver and/or transmitter in wireless communications circuitry **34** (FIG. **3**) such as receiver **35**, wireless local area network transceiver **36** (e.g., a transceiver operating at 2.4 GHz, 5 GHz, 60 GHz, or other suitable frequency), cellular telephone transceiver **38**, or other radio-frequency transceiver circuitry for receiving and/or transmitting radio-frequency signals.

Signal path **44** may include one or more transmission lines such as one or more segments of coaxial cable, one or more segments of microstrip transmission line, one or more segments of stripline transmission line, or other transmission line structures. Signal path **44** may include a positive conductor such as positive signal line **44**A and may include a ground conductor such as ground signal line **44**B. Antenna **40** may have an antenna feed such as feed **92** with a positive antenna feed terminal (+) and a ground antenna feed terminal (−). If desired, circuitry such as filters, impedance matching circuits, switches, amplifiers, and other circuits may be interposed within path **44**.

FIG. **5** is a diagram showing how structures such as peripheral conductive member segment **16'** of FIG. **3** may be used in forming antenna **40**. In the illustrative configuration of FIG. **5**, antenna **40** includes antenna resonating element **90** and antenna ground **52**. Antenna resonating element **90** may have a main resonating element arm portion formed from peripheral conductive member **16'** (e.g., a segment of peripheral conductive member **16** of FIG. **1**). Gaps such as gaps **18**A and **18**B may be interposed between the ends of resonating element arm structure **16'** and ground **52** and may be associated with respective capacitances C**1** and C**2**. Short circuit branch **94** (sometimes referred to as a return path for antenna **40**) may be coupled between arm structure **16'** and ground **52**. Antenna feed branch (antenna feed) **92** may be coupled between arm structure **16'** and ground **52** in parallel with short circuit branch **94**. Antenna feed branch **92** may include a positive antenna feed terminal (+) and a ground antenna feed terminal (−). As described in connection with FIG. **4**, lines **44**A and **44**B in signal path **44** may be respectively coupled to terminals (+) and (−) in antenna feed **92**.

Resonating element arm structure **16'** may have a longer portion (arm) that is associated with a low band resonance LB and that can be used for handling low band wireless communications. Resonating element arm **16'** may also have a shorter portion (arm) that is associated with a high band resonance HB and that can be used for handling high band wireless communications. The low band portion of resonating element arm structure **16'** may, for example, be used in handling signals at frequencies of 700 MHz to 960 MHz (as an example). The high band portion of arm structure **16'** may, for example, be used in handling signals at frequencies of 1710 MHz to 2700 MHz (as an example).

A graph in which antenna performance (e.g., standing wave ratio SWR) for antenna **40** has been plotted as a function of operating frequency f is shown in FIG. **6**. As shown in FIG. **6**, antenna **40** may exhibit a low band resonance LB and a high band resonance HB. As indicated by arrows **100**, antenna tuning may be used to ensure that antenna **40** covers low band LB and/or high band HB. Low band LB may lie in a frequency range of about 700 MHz to 960 MHz and high band HB may lie in a frequency range of about 1710 MHz to 2700 MHz. These are merely illustrative low band and high band frequencies of operation for antenna **40**. In general, antenna **40** may be configured to handle any suitable frequencies of interest for device **10**. If desired, one or more adjustable inductors or other tunable circuit elements may be incorporated into antenna **40** to help antenna **40** cover bands LB and HB (e.g., to tune antenna **40** as indicated by arrows **100**).

When tuning is used, antenna **40** may exhibit an antenna resonance that is narrower than the desired frequency band of interest. For example, the resonance in band LB may be narrower than the width of band LB. Tuning of the LB resonance may then be used to ensure that antenna **40** can handle all desired frequencies in band LB. Similarly, the bandwidth of the antenna resonance in band HB may be narrower than band HB, but antenna tuning may be used to move the antenna resonance in band HB as needed during operation to ensure that antenna **40** can cover all frequencies of interest in band HB.

Adjustable components may be controlled by control circuitry such as storage and processing circuitry **28** of FIG. **2**. During operation of device **10**, control circuitry **28** may make antenna adjustments by providing control signals to adjustable components such as adjustable inductors, adjustable capacitors, adjustable resistors, switches, switches in adjustable inductors, adjustable capacitors, and adjustable resistors, adjustable components such as variable inductors, varactors, and variable resistors, adjustable circuits that include combinations of two or more of these components and/or fixed inductors, capacitors, and resistors, or by providing control signals to other adjustable circuitry. Antenna frequency response adjustments may be made in real time in response to information identifying which communications bands are active, in response to feedback related to signal quality or other performance metrics, sensor information, or other information.

Antenna **40** may, if desired, include one or more adjustable inductor circuits that are controlled by control circuitry **28**. FIG. **7** is a schematic diagram of illustrative adjustable inductor circuitry **110** of the type that may be used in tuning antenna **40**. In the FIG. **7** example, adjustable inductor circuitry **110** can be adjusted to produce different amounts of inductance between terminals **122** and **124**. Switch **120** is controlled by control signals on control input **112**. When switch **120** is placed in a closed state, inductor L is switched into use and adjustable inductor **110** exhibits an inductance L between terminals **122** and **124**. When switch **120** is placed in an open state, inductor L is switched out of use and adjustable inductor **110** exhibits an open circuit between terminals **122** and **124**.

FIG. **8** is a schematic diagram of adjustable inductor circuitry **110** in a configuration in which multiple inductors are used in providing an adjustable amount of inductance. Adjustable inductor circuitry **110** of FIG. **8** can be adjusted to produce different amounts of inductance between terminals **122** and **124** by controlling the state of switching circuitry such as switch **120** (e.g., a single pole double throw switch) using control signals on control input **112**. For example, control signals on path **112** may be used to switch inductor L**1** into use between terminals **122** and **124** while switching inductor L**2** out of use, may be used to switch inductor L**2** into use between terminals **122** and **124** while switching inductor L**1** out of use, may be used to switch both inductors L**1** and L**2** into use in parallel between terminals **122** and **124**, or may be used to switch both inductors L**1** and L**2** out of use. The switching circuitry arrangement of adjustable inductor **110** of FIG. **8** is therefore able to produce inductance values such as L**1**, L**2**, an inductance value associated with operating L**1** and L**2** in parallel, and an open circuit (when L**1** and L**2** are switched out of use simultaneously).

Antenna **40** may include a parasitic antenna resonating element. The parasitic antenna element may, for example, be used to enhance the frequency response of antenna **40** in high band HB (as an example). Tuning circuitry may be used to tune the resonant behavior of the parasitic antenna resonating element and thereby tune the performance of antenna **40** in high band HB.

FIG. **9** is a diagram of an illustrative antenna of the type that may be implemented using a parasitic antenna resonating element. As shown in FIG. **9**, dual arm inverted-F antenna resonating element **90** may be formed from portions of peripheral conductive housing structures **16**. In particular, resonating element arm portion (arm) **202** for producing an antenna response in a high band (HB) frequency range and resonating element arm portion (arm) **200** for producing an antenna response in a low band (LB) frequency range may be formed from respective portions of peripheral conductive housing structures **16**. Antenna ground **52** may be formed from sheet metal (e.g., one or more housing midplate members and/or a rear housing wall in housing **12**), may be formed from portions of printed circuits, may be formed from conductive device components, or may be formed from other metal portions of device **10**.

Antenna **40** may be fed by an antenna feed coupled in feed path **92**. Feed path **92** may include an antenna feed formed from antenna feed terminals such as positive antenna feed terminal (+) and ground antenna feed terminal (−). Transmission line **44** (FIG. **4**) may have a positive signal line coupled to terminal (+) and a ground signal line coupled to terminal (−). Impedance matching circuits and other circuitry (e.g., filters, switches, etc.) may be incorporated into feed path **92** or transmission line **44**, if desired.

Optional inductors such as inductors L' and L" (e.g., fixed inductors or tunable inductors) may be coupled across gaps **18**A and **18**B to counteract the capacitances (C**1** and C**2**) associated with gaps **18**A and **18**B and thereby ensure that antenna **40** operates at frequencies of interest (i.e., so that antenna **40** exhibits a low band response above 690 MHz). Short circuit path **94** may be used to short resonating element arm **202** to ground **52** or may be omitted (e.g., in a configuration in which inductor L" is used to form a return path for antenna **40**).

Adjustable inductor **110-1** may have switching circuitry such as switch **120-1** that receives control signals from control circuitry **28** on input **112-1**. When inductor L is switched into use, antenna **40** may be configured so that the low band resonance of antenna **40** covers an upper portion of low band LB (e.g., frequencies up to 960 MHz). When inductor L is switched out of use, antenna **40** may be configured so that the low band resonance of antenna **40** covers a lower portion of low band LB (e.g., frequencies down to about 700 MHz). If desired, other types of tunable circuitry may be used in adjusting the low band performance of antenna **40**. The use of an inductor such as adjustable inductor **110-1** that is coupled between resonating element **90** and ground **52** to tune the performance of antenna **40** in low band LB is merely illustrative.

Parasitic antenna resonating element **204** may have an L-shape or other suitable shape. Parasitic antenna resonating element **204** may be, for example, a parasitic monopole antenna resonating element having a first end such as end **206** that is coupled to ground **52** and a second end such as end **208** that is floating in opening **82**. The length of monopole antenna resonating element **204** may be approximately a quarter of a wavelength at frequencies of interest (i.e., frequencies in band HB where it is desired to use the antenna resonance associated with parasitic antenna resonating element **204** to enhance antenna performance).

Parasitic antenna resonating element **204** may have tunable circuitry such as adjustable inductor **110-2**. Inductor **110-2** may be adjusted by commands on input **112-2**. Adjustable inductor **110-2** may have multiple inductors and switching circuitry that can be configured to selectively switch the inductors in and out of use to produce a desired amount of inductance between terminals **122-2** and **124-2**. Adjustable inductor **110-2** may, for example, have switching circuitry such as switching circuitry **120** of FIG. **8** and a pair of inductors such as inductors L**1** and L**2** of FIG. **8** (as an example).

Adjustments to inductor **110-2** may be used to adjust the performance of antenna **40**. For example, adjusting the inductance value produced by adjustable inductor **110-2** in parasitic antenna resonating element **204** may adjust the position of a high band antenna resonance located in high band HB of FIG. **6**, as indicated by arrow **100** in high band HB. Inductors such as inductor **110-2** and/or inductor **110-1** may be implemented using fixed inductors or other types of adjustable circuitry can be used to tune antenna **40**. The use of adjustable inductors to tune antenna **40** of FIG. **9** is merely illustrative.

If desired, antenna **40** may contain a parasitic loop antenna resonating element, as indicated by illustrative antenna **40** of FIG. **10**. A shown in FIG. **10**, antenna **40** may have parasitic loop antenna resonating element **220**. Parasitic loop antenna resonating element **220** may have a first end such as end **224** that is coupled to ground **52** at a first location and may have a second end such as end **226** that is coupled to ground **52** at a second end such as end **226**. Parasitic loop antenna resonating element **220** may be electromagnetically coupled (near field coupled) to antenna resonating element **90**, as indicated by coupled electromagnetic fields **222** in FIG. **10**.

Antenna **40** of FIG. **10** may have a resonating element such as dual arm inverted-F antenna resonating element **90** that is formed from portions of peripheral conductive housing structures **16**. Resonating element arm portion **202** may produce an antenna response in high band HB and resonating element arm portion **200** may produce an antenna response in a low band LB. Antenna **40** may also have antenna ground **52**. Antenna ground **52** may be formed from sheet metal (e.g., one or more housing midplate members and/or a rear housing wall in housing **12**), may be formed from portions of printed circuits, may be formed from conductive device components, or may be formed from other metal portions of device **10**.

Antenna **40** may be fed by an antenna feed coupled in feed path **92**. Feed path **92** may include an antenna feed formed from antenna feed terminals such as positive antenna feed terminal (+) and ground antenna feed terminal (−). Transmission line **44** (FIG. **4**) may have a positive signal line coupled to terminal (+) and a ground signal line coupled to terminal (−). Impedance matching circuits and other circuitry (e.g., filters, switches, etc.) may be incorporated into feed path **92** or transmission line **44**, if desired.

As with inductors L' and L" in antenna **40** of FIG. **9**, optional inductors in antenna **40** of FIG. **10** such as inductors L' and L" may be coupled across gaps **18**A and **18**B to counteract the capacitances (C**1** and C**2**) associated with gaps **18**A and **18**B and thereby ensure that antenna **40** operates at frequencies of interest (i.e., so that antenna **40** exhibits a low band response above 690 MHz). Short circuit path **94** may be used to short resonating element arm **202** to ground **52** or may be omitted (e.g., in a configuration in which inductor L" is used to form a return path for antenna **40**).

Low band tuning for antenna **40** of FIG. **10** may be implemented using tunable circuitry such as adjustable inductor **110-1**. Adjustable inductor **110-1** may have switching circuitry such as switch **120-1** that receives control signals from control circuitry **28** on input **112-1**. When inductor L is switched into use, antenna **40** may be configured so that the low band resonance of antenna **40** covers an upper portion of low band LB (e.g., frequencies up to 960 MHz). When inductor L is switched out of use, antenna **40** may be configured so that the low band resonance of antenna **40** moves to lower frequencies and covers a lower portion of low band LB (e.g., frequencies down to about 700 MHz). If desired, other types of tunable circuitry may be used in adjusting low band performance. The use of adjustable inductor **110-1** to tune the performance of antenna **40** of FIG. **10** in low band LB is merely illustrative.

The length of parasitic loop antenna resonating element **220** may be configured to exhibit an antenna resonance at frequencies of interest (i.e., frequencies in band HB where it is desired to use the antenna resonance associated with parasitic loop antenna resonating element **220** to enhance antenna performance).

Parasitic loop antenna resonating element **220** may have tunable circuitry such as adjustable inductor **110-2**. Control signals from control circuitry **28** may be applied to input **112-2** to adjust inductor **110-2**. Adjustable inductor **110-2** may have multiple inductors and switching circuitry that can be configured to selectively switch the inductors in and out of use to produce a desired amount of inductance between terminals **122-2** and **124-2**. Adjustable inductor **110-2** may, for example, have switching circuitry such as switching circuitry **120** of FIG. **8** and a pair of inductors such as inductors L**1** and L**2** of FIG. **8** (as an example). Adjustments to inductor **110-2** may be used to adjust the performance of antenna **40** of FIG. **10**. For example, adjusting the inductance value produced by adjustable inductor **110-2** in parasitic loop antenna resonating element **220** may tune the position of a high band antenna resonance located in high band HB of FIG. **6**, as indicated by arrow **100** in high band HB. Inductors such as inductor **122-2** and/or inductor **110-1** may be implemented using fixed inductors or other types of adjustable circuitry can be used to tune antenna **40**. The use of adjustable inductors to tune antenna **40** of FIG. **10** is merely illustrative.

The foregoing is merely illustrative of the principles of this invention and various modifications can be made by those skilled in the art without departing from the scope and spirit of the invention.

What is claimed is:

1. An electronic device, comprising:

control circuitry;

an antenna that is tuned by the control circuitry, wherein the antenna has an antenna resonating element and an antenna ground configured to resonate in at least a first communications band and a second communications band that is higher in frequency than the first communications band, and the antenna has a parasitic monopole antenna resonating element; and

a peripheral conductive housing member, wherein the antenna resonating element comprises a portion of the peripheral conductive housing member.

2. The electronic device defined in claim **1** further comprising an adjustable electrical component in the parasitic monopole antenna resonating element that is adjusted by the control circuitry.

3. The electronic device defined in claim **2** wherein the adjustable electrical component comprises an adjustable inductor.

4. The electronic device defined in claim **1** wherein the peripheral conductive housing member is separated from the antenna ground by an opening and wherein the parasitic monopole antenna resonating element is located in the opening.

5. The electronic device defined in claim **4** wherein the parasitic monopole antenna resonating element comprises an L-shaped resonating element having a first end coupled to the antenna ground and an opposing second end that is floating in the opening.

6. An electronic device, comprising:

control circuitry;

an antenna that is tuned by the control circuitry, wherein the antenna has an antenna resonating element and an antenna ground configured to resonate in at least a first communications band and a second communications band that is higher in frequency than the first communications band, and the antenna has a parasitic monopole antenna resonating element;

an adjustable electrical component in the parasitic monopole antenna resonating element that is adjusted by the control circuitry, wherein the adjustable electrical component comprises an adjustable inductor; and

an additional adjustable inductor coupled between the antenna resonating element and the antenna ground, wherein the adjustable inductor tunes the antenna in the second communications band and the additional adjustable inductor tunes the antenna in the first communications band.

7. The electronic device defined in claim **6** further comprising:

a first gap between the antenna resonating element and the antenna ground that is associated with a first capacitance;

a first inductor coupled across the first gap;

a second gap between the antenna resonating element and the antenna ground that is associated with a second capacitance; and

a second inductor that is coupled across the second gap.

8. The electronic device defined in claim **7** wherein the antenna resonating element comprises a dual arm inverted-F antenna resonating element, the electronic device further comprising an antenna feed coupled between the antenna ground and the dual arm inverted-F antenna resonating element.

9. An electronic device, comprising:

control circuitry; and

an antenna that is tuned by the control circuitry, wherein the antenna has an antenna resonating element and an antenna ground configured to resonate in at least a first communications band and a second communications band that is higher in frequency than the first communications band, the antenna has a parasitic loop antenna resonating element, and the parasitic loop antenna resonating element has a first end that is coupled to the antenna ground and a second end that is coupled to the antenna ground.

10. The electronic device defined in claim **9** further comprising an adjustable inductor in the parasitic loop antenna resonating element that is adjusted by the control circuitry to tune the antenna.

11. The electronic device defined in claim **10** further comprising a peripheral conductive housing member, wherein the antenna resonating element comprises a portion of the peripheral conductive housing member.

12. An electronic device, comprising:

control circuitry;

an antenna that is tuned by the control circuitry, wherein the antenna has an antenna resonating element and an antenna ground configured to resonate in at least a first communications band and a second communications band that is higher in frequency than the first communications band, and the antenna has a parasitic loop antenna resonating element; and

a peripheral conductive housing member that is separated from the antenna ground by an opening, wherein the antenna resonating element is formed from a segment of the peripheral conductive housing member, and the loop antenna resonating element is located in the opening.

13. The electronic device defined in claim **12** further comprising:

a first adjustable inductor in the parasitic loop antenna resonating element that is adjusted by the control circuitry to tune the antenna in the second communications band; and

a second adjustable inductor that couples the peripheral conductive housing member to the antenna ground and that is adjusted by the control circuitry to tune the antenna in the first communications band.

14. The electronic device defined in claim **13** wherein the peripheral conductive housing member has at least one end that is separated from the antenna ground by a gap, the electronic device further comprising an inductor that is coupled across the gap.

15. An antenna, comprising:

an inverted-F antenna resonating element;

an antenna ground;

a parasitic antenna resonating element; and

an adjustable inductor in the parasitic antenna resonating element that tunes the antenna, wherein the inverted-F antenna resonating element comprises a portion of a peripheral conductive electronic device housing structure.

16. The antenna defined in claim **15** wherein the antenna is configured to operate in a first communications band and a second communications band at higher frequencies than the first communications band, wherein the parasitic antenna resonating element comprises a parasitic monopole antenna resonating element, and wherein the adjustable inductor tunes the antenna in the second communications band.

17. The antenna defined in claim **15** wherein the antenna is configured to operate in a first communications band and a second communications band at higher frequencies than the first communications band, wherein the parasitic antenna resonating element comprises a parasitic loop antenna resonating element, and wherein the adjustable inductor tunes the antenna in the second communications band.

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